

Consequences of Forest Management on Soil–Tree Relationships

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I. INTRODUCTION

Plantation management practices affect and alter many processes occurring in forests. Events triggering these changes occur throughout the rotation,

from site preparation to final harvest. Preparation for planting may involve collecting and burning of previous crop residues, ploughing, scalping and chemical treatments, all of which alter physical, chemical, hydrological and biological properties of the site. The tree species planted and their spacing affect uptake of nutrients, the quantity and quality of litter that forms, its rate of decay and recirculation of nutrients. Plantations may be burned by prescription, thinned or fertilized—thereby altering physical, chemical and biological properties of surface soil. Harvest, particularly at clear felling, redistributes forest biomass, alters temperature and water balances, and causes substantive changes in chemical and physical site properties and processes.

Consequences of plantation practices depend on characteristics of the site and stand, and on the nature and timing of operations. Forestry management practices affecting physical, chemical, hydrological and biological ecosystem properties and their consequences are the topics of this chapter.

II. SITE PREPARATION

Preparing sites for planting carries greater potential than any other single forest management practice for causing lasting changes in soil–tree relationships. Methods used in site preparation fall into two main categories: (i) mechanical repositioning of surface materials; and (ii) residue reduction by prescribed burning. Both categories alter soil nutrient distribution and availability, but their consequences have been critically examined only recently.

A. Mechanical Repositioning of Materials

The forest floor is an important nutrient reserve, particularly in temperate and boreal forests where its nitrogen content equals or exceeds that in the living, above-ground biomass (Fig. 1). Because microbial decomposition of organic matter relates directly to temperature with a Q_{10} of about 2 for organic N (Powers, 1980), floors of boreal and cool temperate forests may contain up to 3 times more N than is stored in mineral soil (Williams and Dyrness, 1967; Wells and Jorgensen, 1979). However, that same reserve presents a formidable barrier to successful regeneration when covered by unwanted vegetation, or when augmented by logging debris. Blading, chipping, chopping, ploughing and discing by heavy machinery are common methods used in preparing planting sites.

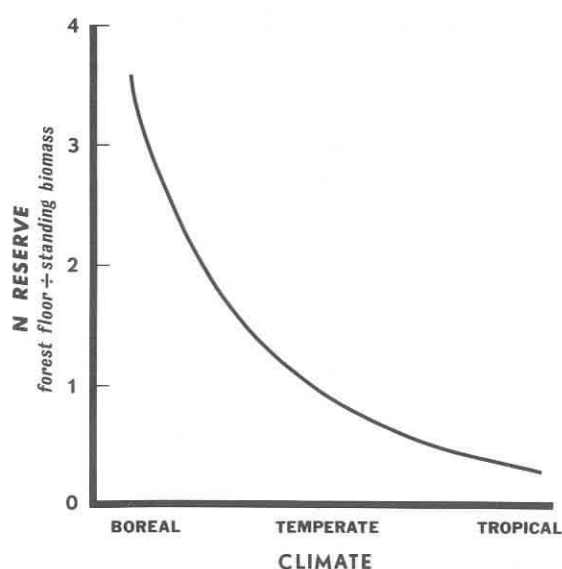


Fig. 1. Proportion of N stored in the forest floor relative to that stored in the standing biomass ("N Reserve") by climatic forest type. Basis: 24 stands reported in the literature.

Mechanical site preparation can lead to nutrient loss, both through increased erosion, and leaching to ground water. Results on the Coastal Plain region of the southern USA showed that sediment yields in run-off were increased by 14.1, 14.3 and 19.0 t ha⁻¹ from chopping, shearing and contour bedding respectively, on 30 to 50% slopes (Beasley, 1979). In another study, (Burger and Pritchett, 1979), timber harvest, burning and blading removed 416 kg N ha⁻¹, virtually all the above-ground N of a *Pinus elliottii* var. *elliottii*, *P. palustris* (slash-longleaf pine) stand located on arid sand of the lower coastal plain near Gainesville, Florida. Discing and bedding mixed remaining organic matter with surface horizons of soil, increasing mineralization. Soil solution nutrient concentrations in the rooting zone rose from 0.08 to 0.16 mg N l⁻¹ for NH₄⁺, 0.09 to 0.13 mg N l⁻¹ for NO₃⁻, 0.05 to 0.68 mg l⁻¹ for P and 0.57 to 2.83 mg l⁻¹ for K, compared with a burned and chopped site. A similar study in a Wyoming *Pinus contorta* (lodgepole pine) clearcut showed soil solution NO₃⁻ concentrations more than an order of magnitude greater in windrowed areas than in the uncut forest 6 years after harvest (Hart *et al.*, 1980) (Table I). Concentrations of K, Mg and Ca also increased greatly.

Incorporating high carbon woody residues into surface soil during site preparation should not affect the mineralization of leafy residues and mobilization of nutrients unless the woody material is finely divided.

Table I. Average yearly concentrations of materials in soil solution on a *Pinus contorta* site on a loamy glacial till in Wyoming.^a

Years since harvest	Annual average concentration soil solution (mg l ⁻¹)					
	Uncut forest	Complete utilization		Conventional harvest		
		Bare ground	Chip mulch	Broadcast burn	Between windrows	Beneath windrows
Nitrate-N						
2	0.09	1.46	0.52	0.31	0.31	^b
4	0.12	0.40	0.38	0.73	0.39	0.66
6	0.23	1.39	2.32	4.00	2.74	9.50
Potassium						
2	0.6	1.2	1.7	1.6	0.9	^b
4	0.4	0.6	1.7	1.1	0.7	1.9
6	0.6	0.5	1.5	1.1	1.6	2.1
Magnesium						
2	0.8	1.8	2.4	2.5	1.3	^b
4	0.4	0.6	1.4	0.7	0.9	3.0
6	0.6	0.6	1.2	1.2	1.2	4.3
Calcium						
2	2.9	6.9	10.0	9.7	4.9	^b
4	1.5	2.2	6.4	2.0	3.2	11.0
6	2.7	2.8	5.9	4.4	4.8	14.8
Total phenols						
2	0.010	0.188	0.622	0.037	0.000	^b
4	0.000	0.000	0.002	0.000	0.000	0.004
6	^b	^b	^b	^b	^b	^b

^a From Hart *et al.* (1980).

^b Not measured.

Chipped slash may, if worked into the soil, result in C:N ratios unfavourable to N mobilization, or may leach antibiotic compounds affecting nitrification. In Wyoming, NO₃⁻ concentrations in soil water beneath mulched logging slash, averaged only one-fifth of those beneath a site where slash had been removed, and one-fourth of those beneath a broadcast-burned site by the second year (Hart *et al.*, 1980) (Table I). Concentrations of total phenols in soil solution beneath mulched sites averaged 3.3 times greater than beneath bare sites and 16.8 times greater than beneath broadcast burned sites, suggesting that phenolics leached from residues inhibited nitrifier activity. Phenolic compounds are known biotoxins (Heal, 1979) and are present in unusually large amounts in conifer wood. Bollen and Lu (1969) proposed

leaving as much bark as possible after logging so that its high tannin content might inhibit nitrification and help conserve N.

Although repeated litter removal clearly has deleterious effects on site quality (Baule and Fricker, 1970; Kreutzer, 1972), few studies have assessed the effect of forest floor removal on growth of the next stand. In Ontario, Mullin and Campbell (1975) found that trees grown for 10 years on scalped soils were as much as 20% shorter than on adjacent, unscalped sites. Seedlings of *Picea abies* (Norway spruce) grown for 9 years on a northeastern USA clearcut which had been scalped of slash and litter were 40 cm (32%) shorter than seedlings grown within 2 m of undisturbed litter (Nyland *et al.*, 1979). Foliar analyses of seedlings from litter-free areas showed strong N deficiency (0.88% *vs* 1.50%), and significantly lower concentrations of P, K, Ca, Mn and Fe.

The effect of surface soil stripping, used frequently in removing sprouting species and dormant weed seeds in litter and surface soil, compounds the nutritional problem of forest floor removal. In New Zealand, stripping an estimated 2.5 cm of pumice topsoil into windrows produced interwindrow stands of *Pinus radiata* (radiata pine) with only 60% ($20.5 \text{ m}^3 \text{ ha}^{-1}$) of the volume on unstripped sites ($34.3 \text{ m}^3 \text{ ha}^{-1}$) after 7 years (Ballard, 1978a). Although windrow-planted trees averaged 0.01 m^3 more in volume and 19% greater growth than those on unstripped sites, productivity still was one-fifth less than in unstripped sites, projecting to a $50 \text{ m}^3 \text{ ha}^{-1}$ yield deficit at rotation age 26 years. An estimated topsoil loss of 26 cm from deep ripping reduced the yields to only 15% of controls ($5.2 \text{ m}^3 \text{ ha}^{-1}$ *vs* $34.3 \text{ m}^3 \text{ ha}^{-1}$), at age seven. Foliar concentrations of N and B were also lowered by topsoil loss, as was total N and exchangeable Mg in surface soils.

B. Prescribed Burning

The intensity of burning of forest fuels is seldom measured directly, but can be estimated from the residue condition (Boyer and Dell, 1980). During pyrolysis, organically bound nutrients—particularly N and S—are oxidized rapidly once temperatures reach 200°C , with losses as volatiles or fly ash increasing proportionally with burning intensity (Table II). Losses, both proportional and absolute, are greater during typical logging and piled-thinning slash burns, than during the relatively light understory burns in stands. Although logging-slash burns cause immediate losses of nutrients, the effects are not necessarily lasting. Kramer and Hermann (1979) studying 25-year-old unburned and broadcast burned *Pseudotsuga menziesii* (Douglas fir) clearcuts in Oregon and Washington, detected no significant differences

Table II. Nutrient loss as volatiles and fly ash for different fire intensities and forest fuel conditions.

Fire intensity	Fuel	Fuel load (t ha ⁻¹)	Amount consumed (%)	Nutrient loss (kg ha ⁻¹)						Reference
				N	P	K	Ca	Mg	S	
Severe	Understory (<i>Pinus ponderosa</i>)	52.9	98	446 (99) ^a	—	—	—	—	—	Klemmedson <i>et al.</i> , 1962
Severe	Wildfire (Mixed forest)	70.6	96	817 (97)	—	270 (79)	76 (19)	24 (31)	—	Grier, 1975
Severe	Piled thinning slash (<i>Pinus ponderosa</i>)	17.3	85	59 (86)	—	—	—	—	—	Klemmedson, 1976
Severe	Logging slash (<i>Pinus radiata</i>)	79.5	84	220 (72)	8 (27)	21 (21)	123 (31)	13 (16)	5 (30)	Flinn <i>et al.</i> , 1979
Severe	Piled thinning slash (<i>Pinus ponderosa</i>)	28.2	80	91 (88)	—	—	—	—	—	Klemmedson, 1976
Moderate	Logging slash (Mixed forest)	630.0	51	—	10 (18)	5 (17)	100 (21)	37 (29)	—	Harwood and Jackson, 1975
Moderate	Logging slash (<i>Pseudotsuga/Larix</i>)	161.1	33	106 (11)	—	—	—	—	—	Jurgensen <i>et al.</i> , 1981
Moderate	Understory (<i>Pinus ponderosa</i>)	52.9	27	142 (32)	—	—	—	—	—	Klemmedson <i>et al.</i> , 1962
Moderate	Understory (<i>Pinus ponderosa</i>)	27.0	21	129 (38)	^b	^b	22 (11)	^b	16 ^c (43)	Nissley <i>et al.</i> , 1980
Moderate	Logging slash (Mixed forest)	54.0	20	166 (20)	6 (9)	^b	^b	^b	—	Skoklefald, 1973

^a Figures in parenthesis are the percent of the total.

^b Slight increases.

^c Data from 2 plots only.

in surface soil concentrations of N, P, K or Ca, although concentrations of N and organic matter tended to be lower on severely burned sites.

Prescribed burns of low intensity often cause small but measurable short-term gains in surface soil N through ammonification (Vlamis *et al.*, 1955, Neal *et al.*, 1965), and P (Tarrant, 1956). Thermal ammonification of organic N begins at temperatures as low as 100°C, increases rapidly between 200° and 300°C, and decreases thereafter (Dunn and DeBano, 1977). Nitrate is not formed directly from pyrolysis, but high NH_4^+ substrate levels and raised soil pH favour rapid nitrification. Seedlings planted in ash beds grow faster, partly because of reduced weed competition, but also because of increased nutrient availability and mycorrhizal development. Powers and McColl (unpublished) found that *Pinus ponderosa* (ponderosa pine) planted in burned windrows had double the seedling biomass, triple the root length, and twice the number of mycorrhizal infections per seedling after one growing season as those planted in adjacent, unburned clearcuts. Soil solutions collected regularly beneath burned windrows had NO_3^- concentrations averaging 9.1 mg N l⁻¹ for the first year, nearly 18 times higher than beneath unburned clearcuts. Hotter burns may increase extractable cations (DeByle, 1976) and mobilize cations in the soil solution through the production of bicarbonate anions (Grier and Cole, 1971).

Generalizations about the affects of prescribed burning must be tempered by the specific properties of each site. In Norway, pine and spruce seedlings planted following burning on productive *Oxalis/Myrtillus* and *Myrtillus* sites grew well and had high foliar N concentrations in the first few years after burning, but were inferior to seedlings on unburned sites in both growth and foliar N by age 12 (Skoklefeld, 1973). On these productive sites, burning the relatively thin humus layers may have increased nutrient leaching of exposed mineral soil in subsequent years. On poorer *Calluna* sites, however, burning the thick, acid layers of heath humus improved height growth and foliar N concentration in planted trees.

III. STAND DEVELOPMENT

A. Physical and Chemical Changes in Soil

Tree species vary greatly in their adaptation to soil conditions and this can be used to advantage in renovating problem soils. In the Soviet Union, irrigated plantations of *Acacia*, *Acer*, *Halimodendron* and *Ulmus* have been used to rehabilitate solonetz-like soils. Saline conditions had disappeared in 50-year-old plantations that had been irrigated twice-yearly for the first 30

years (Biryukova, 1958). Depth of the A horizon increased in that period from 14 to 20–30 cm. Soil porosity, permeability and leaching of soluble salts increased as well, with greater leaching under *Acer* and *Ulmus* than under *Acacia*. Plantings of conifers tolerant of waterlogging, such as *Picea sitchensis* (Sitka spruce), reduce perched water tables both through transpiration and canopy interception. In Great Britain, *Picea* plantations intercept an estimated 40% of the summer rainfall (Pyatt and Craven, 1979). However, the same properties lowering water tables on wet sites also reduce water yields from normal sites (see Chapter 2). Waterflow from conifer plantations may be 20% less than from deciduous hardwood plantations (Nutter, 1979).

Afforesting sites naturally low in fertility, or lowered because of overuse, usually increases the organic matter in mineral soil. As a canopy develops, litter production increases, humidity rises and both diurnal and seasonal temperature variations narrow in the forest floor, stimulating litter decomposition and nutrient release (Heal, 1979; Chapter 2). In Illinois, plantings of four pine species in old agricultural fields on a silt loam increased soil organic matter by 75% in the top 15 cm soil layer over an 18-year period (Gilmore and Boggess, 1976). Sandy loam surface soils in abandoned Wisconsin fields planted to *Pinus resinosa* (red pine) showed steady increases in organic matter of 0.06% yr^{-1} for a 50 year period (Wilde, 1964).

Converting deciduous hardwood sites to pine plantations usually has no appreciable effect on soil pH or fertility (Lane, 1975). However, studies on coarse-textured Australian soils supporting evergreen hardwoods show a different pattern: *P. radiata* planted for 19 to 30 years on podzolized sands cleared of dry sclerophyll forest showed 37–60% decreases in surface soil organic C and bulk density increases of 7–20% (Hamilton, 1965). Differences were small on wet sclerophyll and woodland sites, however, suggesting that pine litter decomposition and incorporation is retarded on dry sites, compared with native vegetation litter (see Chapter 5). A similar study comparing planted *Pseudotsuga menziesii* and native *Eucalyptus* growing on granite showed a redistribution of organic matter and nutrients, rather than a loss (Turner and Kelly, 1977). Soil beneath *Pseudotsuga* had a higher pH (5.7 vs 5.2), Ca, Mg and K in the surface layers and higher organic matter content at depth. Water extracts of litter indicated that chelation and leaching potential were greatest beneath native *Eucalyptus*, and that *Pseudotsuga* plantings retarded natural podzolization.

Compared with conifers, deciduous angiosperm leaves are relatively rich in bases, and the soil pH may rise beneath hardwoods planted on acid soils, peaking sometime after crown closure (Ovington, 1953). Angiosperm litter tends to be rich in Ca and Mg and leachate, particularly that from ground flora, tends to be neutral in reaction (Table III). *Pinus echinata* (shortleaf pine) introduced to old fields in Illinois had not changed the surface soil pH

Table III. Composition of leaf litter and reaction of their leachate under field conditions.^a

Species	Mineral content (%)		Leachate pH	
	Ash	CaO + MgO	Mean	Range
<i>Prunus padus</i>	14.1	5.7	7.4	6.7–7.7
<i>Sambucus racemosa</i>	13.3	5.4	7.4	6.7–7.7
<i>Sorbus aucuparia</i>	6.0	3.5	7.2	6.6–7.4
<i>Corylus avellana</i>	10.6	4.7	7.1	6.2–7.4
<i>Viburnum opulus</i>	6.4	2.9	7.0	5.5–7.8
<i>Betula verrucosa</i>	7.9	3.0	6.8	—–7.1
<i>Picea excelsa</i>	7.1	2.2	6.4	5.5–7.0
<i>Quercus pedunculata</i>	8.0	2.3	6.3	5.6–6.9
<i>Pinus sylvestris</i>	2.5	1.3	5.7	5.5–6.8

^a From Stepanov (1932).

from its natural value of 5.0 after 30 to 35 years, although exchangeable Ca had increased at all depths (Rolfe and Boggess, 1973). In contrast, soils beneath hardwoods with ground flora had lower bulk densities, higher pH (5.5), and about twice the organic matter and exchangeable Ca in the surface horizon.

One of the earliest nutrient changes in soils following planting of trees concerns soil N. Concentrations of NH_4^+ , NO_3^- , and HF-extractable N and extractable P were greater in surface soil beneath and near 10–14 year old *Pinus* and *Larix* than in abandoned fields nearby in studies by Fisher and Stone (1969). Concentrations peaked in the spring, and averaged 9.9 ppm $\text{NH}_4\text{-N}$, 3.5 ppm $\text{NO}_3\text{-N}$ and 2.0 ppm P in the top 5 cm of soil beneath tree crowns, compared with 1.5, 1.5 and 0.5 ppm, respectively, in the open. Foliar concentrations of N and P also were higher in successive croppings of herbs growing beneath trees, averaging 1.90% N and 0.24% P, compared with 1.42 and 0.20% for field-grown herbs. Fisher and Eastburn (1974) found less-striking differences beneath 20-year-old plantations of *Pinus* and *Larix* and adjacent abandoned fields. Plantation soils had more total N and amino-N, but less hydrolysable-N than field soils. Bulk density, organic carbon, pH, and exchangeable cations were unaffected. Soil characteristics beneath *Tilia americana* matched those for old field soils, indicating that plantation effects on soil N are not general for all trees. Lodhi (1977) found greater NH_4^+ concentrations (10.2 ppm N vs 7.7 ppm N) and higher $\text{NH}_4^+:\text{NO}_3^-$ ratios (6.2 vs 3.3) in soil beneath crowns of Missouri deciduous hardwoods than beneath herbaceous vegetation, and attributed it to litter extractives suppressing nitrification.

B. Microbiological Changes

Soil micro-organisms are influenced greatly by aeration, and poorly drained soils planted to trees will shift from populations of anaerobes to aerobes as surface profiles dry. Activity of fungi, more important than bacteria in breaking down surface residues under aerobic acid conditions (Alexander, 1961), will increase and dominate in degrading pre-existing surface materials. However, Gadgil and Gadgil (1975) suggested that mycorrhizal fungi may retard decomposition of surface litter perhaps by competition with saprophytic micro-organisms for nutrients or by physical exclusion.

Studies of podzolized heathland soils in Germany forested with mixed stands of *Quercus* and *Betula*, and pure plantations of *Pinus sylvestris* show greatly increased numbers of bacteria in surface and subsoils beneath hardwoods, but not under pine (Burrichter, 1954). Also in Germany, Steubing (1977) found that after a slow start, microbial respiration in litter and humus layers beneath planted *Picea* exceeded that beneath *Fagus* by midsummer. This was attributed to initial inhibition of micro-organisms by high concentrations of tannins and resins beneath *Picea*, followed by a response to higher caloric substrates once the suppressive compounds were neutralized. Changes occur in the dominant mycorrhizal fungi during stand development (Chapter 6).

Tree species vary by one or more orders of magnitude in the production and balance of such root exudates as glucose and sucrose (Smith, 1969), which influences the kind and activity of rhizosphere microbes. In Australia, soils in dry sclerophyll *Eucalyptus* sites cleared, burned and converted to *P. elliotii* plantations were characterized by greater densities of fungi and autotrophic nitrifying bacteria (Jones and Richards, 1977). Twice as many microbial species were isolated from pine soils as from burned *Eucalyptus*. However, species of N-fixing *Beijerinckia* present in the native forest were not found beneath pine. One-third more soil bacteria were present on unburned *Eucalyptus* sites than beneath pines.

IV. STAND TREATMENT

Between establishment and final harvest, plantations usually receive one or more silvicultural treatments to maintain satisfactory stocking and growth. Chief among these are weed and pest control, thinning, burning and fertilization.

A. Weed Control and the Use of Pesticides and Herbicides

Reduced weed competition for water and nutrients generally increases tree growth (Nambiar and Zed, 1980). Releasing *P. ponderosa* from woody shrub competition on two sites in California caused a doubling of height increment on the poorer site, and a two-thirds increase on the better (Table IV). Improved soil and foliar N levels were still evident 5 year after treatment, and pre-dawn xylem moisture stress remained 40 and 11% lower in trees on the poorer and better weeded sites, respectively (see also Chapters 6, 12).

Sutton (1975) found that controlling grass competition with paraquat increased 3-year height growth, an average of 48% for *Picea glauca* (white spruce). Mean foliar concentrations of N, P and K were increased by 2.6, 1.5 and 3.1 times respectively, after the first year on the poorest site, and the advantages continued for 3 years. A response to herbicide application also was shown on a better site, though not to the same degree. Similar results have been obtained with applied pesticides: Bengtson and Smart (1981) found that methyl bromide fumigation and fertilization produced increases of 29% in height and 134% in stemwood volume over untreated controls of *Pinus elliottii*, 13 years after treatments. Unfumigated, unfertilized trees were deficient in K, but soil fumigants enhanced the uptake of K and delayed the onset of deficiency. They concluded that root damage by nematodes contributed to K deficiency and growth decline in pine on Florida sandhills, even when fertilized.

Herbicide effects may exceed those due simply to weed removal. Sands and Zed (1979) noticed such an effect 16 weeks after applying 6 kg ha^{-1} of atrazine to *P. radiata* growing in Mount Burr in South Australia. By 24 weeks, trees treated with atrazine had 34% more top weight than hand-weeded controls. Increases in foliar P, K and N concentrations where atrazine had been applied, suggested that atrazine increased the efficiency of nutrient uptake.

Herbicides and pesticides may have negative side-effects by altering soil microbial balances, particularly where the chemical agent degrades slowly. Degradation varies with the type of chemical and environmental conditions. Norris (1970) studied herbicide breakdown in the forest floor of *Alnus rubra* (red alder) under laboratory conditions. Although degradation was relatively rapid for amitrol and 2,4-D (80 and 90% in 35 days) and 2,4,5-T (87% in 120 days), picloram was degraded slowly (35% in 180 days). Persistence of picloram may be aggravated by the tendency of some species to release some of this chemical through the roots back into the rhizosphere following absorption (Webb and Newton, 1972).

Although concentrations of herbicides in the field seldom exceed levels

Table IV. Five-year effects of fertilization and mechanical brush cleaning on nitrogen and growth characteristics of 15-year-old *Pinus ponderosa* planted on two site qualities in California. The fertilizer used was urea at 224 kg N ha⁻¹. Weed biomass averaged 31 and 42 t ha⁻¹ on the poor and good sites, respectively (Powers, 1983).

Treatment	Poor site ^a				Good site ^b			
	Mineralizable soil N (ppm)	Foliar N		Height increment (m)	Mineralizable soil N (ppm)	Foliar N		Height increment (m)
		Current needles	1-year-old needles (%)			Current needles	1-year-old needles (%)	
Control	2.6	0.87	0.71	0.60	7.1	0.98	0.80	1.44
N only	3.5	0.83	0.76	0.66	9.4	1.05	0.94	2.08
Cleaning only	4.4	0.92	0.78	1.23	9.4	1.14	0.88	2.42
N and cleaning	4.6	0.98	0.86	2.05	11.6	1.26	1.02	3.21

^a Height 15 m at 15 years.

^b Height 30 m at 15 years.

toxic to soil organisms for long periods (Norris, 1975), inhibitory effects have been noted. For example, Eijssackers (1974) found that amitrol, more effective than, 2,4,5-T in controlling *Prunus*, also was more toxic to soil fauna. Eijssackers and Chardon (1979), studying effects of another *Prunus* herbicide, ammonium sulphamate, found it to be harmful to collembola, isopods and millipedes, thus retarding the breakdown of birch litter. Similarly, microbial reactions to herbicides were studied by Amakiri (1980) in teak plantations. *Nitrosomonas* was more sensitive than *Nitrobacter* to chloroxuron, metabromuron and fluometuron. This differential effect would obviously alter availability, mobility and cycling rates of N. Applying the silvicide MSMA directly to the forest floor increased ammonification in litter, but decreased nitrification, as did cacodylic acid (Bollen *et al.*, 1977); however, concentrations of applied chemicals were much greater than normally used. After examining 10 herbicides at dosages used for weed control in nursery beds and broad-leaf evergreen control on reforestation sites, Nakos (1980) concluded that only asulam considerably reduced (>50%) NO_3^- production. This was not considered to be an adverse effect on soil fertility as it helps conserve soil N by avoiding leaching and denitrification of NO_3^- .

Other possible detrimental effects of herbicides include water pollution and toxicity to wildlife and man (Byrnes and Holt, 1975). As noted earlier, in relation to soil micro-organisms, the rate of degradation and the mobility in terms of the rate of leaching in the soil largely determine the relative hazard of herbicides. For example, picloram degrades slowly (Norris, 1970) and is relatively mobile (Norris, 1975), and thus is potentially quite hazardous. Greatest pollution of streams and lakes occurs by direct application to the water surface, rather than by movement in soil and ground water (Norris, 1975).

B. Thinning

Rainfall passing through the crowns of trees is enriched in nutrients (see Chapter 3). Mobile nutrients like N and K reach particularly high concentrations in throughfall relative to precipitation in the open (Wells and Jorgensen, 1975). A direct effect of thinning is to reduce the canopy enrichment effect on throughfall. While the change may be small in absolute quantities of nutrients, it may be significant if the thinnings are removed, for throughfall nutrients are usually readily available for uptake and are concentrated directly beneath crowns where feeder roots are most active (see Chapter 2).

Although thinning operations may decrease soil permeability and water infiltration rate to some degree (Haberland and Wilde, 1961), such effects generally are minor and are restricted to skid trails. More importantly,

thinning increases water availability to the remaining trees by reducing transpiration and increasing throughfall. Nutrient availability also is improved, as shown by foliar nutrient concentrations which may increase proportionately with thinning intensity (Roberge *et al.*, 1970). However, foliar nutrient concentrations may drop for a period after thinning if rates of crown expansion exceed increases in nutrient uptake.

Thinning raises the temperature of the forest floor, stimulating microbial activity if litter does not waterlog, or dry from exposure (Roberge *et al.*, 1970). In Nova Scotia, thinning in *Abies balsamea* (balsam fir) caused forest floor materials to thaw 20 days sooner, decompose faster, and release about twice the NH_4^+ as unthinned plots (Piene, 1978). Haberland and Wilde (1961) found that 35% of the forest litter disappeared in the first 3 years after thinning *P. resinosa*, and that the organic matter content of the top 15 cm soil had decreased from 1.33 to 1.06%. Increased throughfall had leached about twice the K, Ca and Mg from litter in thinned stands as from that in unthinned stands. In a study of *P. taeda* plantation (Wells and Jorgensen, 1975), fresh needle litter in thinned stands held only about half of its original N content 1 year after thinning. In unthinned stands, needles still retained 70–80% of their original N content after 7 years. Thinning had little effect on decomposition rates of needles deposited before thinning. Although thinning increased absolute amounts of N released from decomposing litter, C changed proportionally, so that N concentration varied little from that in unthinned stands (Wells and Jorgensen, 1975).

While temperature and water are important regulators in the biological breakdown of litter, the biochemistry of leaves at leaf fall controls the proportion of N that can be mobilized (see Chapter 5). In normal senescence, soluble N compounds are translocated from the leaf to sites of more active growth or storage (see Chapter 7). Residual proteins then combine with polyphenols to form complexes extremely resistant to microbial attack (Millar, 1974). In contrast, leaves reaching the forest floor in thinnings are 50–100% higher in N concentration (Rodin and Bazilevich, 1967) with much more of the N in soluble, easily degradable forms. Therefore, thinning increases the substrate needed for ammonification by adding large quantities of fresh foliage to the forest floor with the amounts greatest on the best sites. The surplus of NH_4^+ , coupled with a slight increase in pH from bases leaching from litter (Page, 1968) leads to temporary increases in nitrifier activity (see Chapter 5).

C. Prescribed Burning

Prescribed burning effects in established stands (underburning) are less severe than those accompanying slash burning, because of lower burning

intensity (Table II). Prescribed burning rapidly oxidizes the fraction of the forest floor that is normally decayed by micro-organisms at a slower rate (Pritchett, 1979). The materials which remain are woody and humic residues, which decompose slowly. Thus, burning removes the organic matter that contains the most rapidly cycling nutrients in the ecosystem, and leaving the humus. If the burn is not too intense, most of the nutrients remain in the ash layer, and may not be lost from the site. New litter falling the following year resumes the normal cycling sequence.

Heyward and Barnette (1934) studying 18 sites in the *P. palustris* region of the southern USA, found that soils of burned sites had less acidity, and greater extractable Ca, total N, and organic matter than unburned controls, even in sites burned annually. Alban (1977) showed that surface soils in repeatedly burned *P. resinosa* plantations were higher in CEC, pH, N, P, K, Ca and Mg than were unburned sites, and that spring burns produced richer soils than hotter summer burns. Wells (1971) found that southern USA pine stands, underburned repeatedly over 20 years, had less N in the forest floor, but more N in surface soil horizons, so that the total N storage within the forest floor and top 10 cm of soil changed little.

Cycling of nutrients within the ecosystem is altered by prescribed burning, even though there may be no net loss. If the fire scorches tree crowns, litter may fall prematurely. In a Minnesota study (Grigal and McColl, 1975) 3 year total returns of N, P and K were 24, 3 and 5 kg ha⁻¹ greater in burned than in unburned forests because burning caused greater fall of needles with higher nutrient concentrations. Litter decomposition rates, however, were unaltered by burning (Grigal and McColl, 1977).

Prescribed burning can reduce microbial and faunal populations in the litter and the upper few centimetres of soil (Ahlgren, 1974; Viro, 1974), but effects are temporary. Free-living N-fixers may be stimulated by reduced acidity (Viro, 1974), but the consequences are probably not great. Seeds of symbiotic N-fixing species may germinate following seed coat scarification by heat; legumes may be five times more abundant on burned than on unburned sites (Cooper, 1971).

D. Fertilization

The most common fertilizer nutrients applied in forestry are N and P, applied either at planting or at intervals throughout a rotation, depending on the thinning regime (see Chapter 12). Fertilizer effectiveness is relatively short-lived for N. Leaching of NO₃⁻ and eventual immobilization of recycled N fraction in humus and biomass (Miller, 1981) produce fertilizer effects

rarely lasting beyond a decade. Except on sandy soils low in Al and Fe, P is not leached readily from forest soils (Powers, *et al.*, 1975), and effects of the initial application at planting time may last from a few years (Ballard, 1978b) to a full rotation (Pritchett, 1979).

Adding N to the forest floor decreases the C:N ratio of litter and humus, and often accelerates decomposition (Roberge *et al.*, 1970; Turner, 1977). Liming also favours decomposition of acid, nutrient-poor litter of pine (Krapfenbauer and Tuszyński, 1967), and of acid, raw humus of pine stands which have been affected by litter gathering (Baum, 1979). Urea applied to forest floors forms complexes with amino acids, and on alkaline hydrolysis substitutes NH_4^+ for H^+ and divalent cations on carboxyl groups. This causes dissolution and leaching of organic compounds of medium and higher molecular weight, primarily monosaccharides and amino acids (Ogner, 1972). Dissolved organic materials probably do not move far, but are precipitated in lower layers of humus and surface layers of mineral soil where they provide substrates for micro-organisms. However, cations displaced from carboxyl groups by NH_4^+ may be leached to other cation exchange sites, or lost to ground water.

Effects of fertilizers on the forest floor and on soil micro-organisms are varied. Because NH_4^+ is the substrate for nitrifiers, their numbers and activity remain low as long as NH_4^+ is scarce. Additions of NH_4 -forming fertilizers such as urea generally increased numbers and activity of ureolytic bacteria and fungi in the litter and humus (Roberge *et al.*, 1970), and the production of NO_3^- (Nakamura and Powers, 1978), indicating rapid microbial response to excess NH_4^+ (Table V). Accumulations of NO_3^- may reduce the influence of

Table V. Maximum concentrations of NH_4 -N and NO_3 -N in soil solution at 50 cm depth in three soil types up to 2 years after N fertilization.^a

Parent rock	Profile development	Soil solution maximum N concentration (mg l^{-1})			
		NH_4 -N		NO_3 -N	
		Control	224 kg N/ha ⁻¹	Control	224 kg N/ha ⁻¹
Acid igneous	Immature	0.92	4.39	1.09	17.15
	Mature	0.50	1.23	0.48	1.06
Basic igneous	Immature	0.79	3.68	1.70	12.97
	Mature	1.10	0.76	3.18	3.48
Meta-sedimentary	Immature	0.96	0.60	0.78	3.90
	Mature	0.65	1.54	0.21	8.34

^a From Powers (1983). Data from 10 forest installations in California, 224 kg N ha⁻¹ was applied as urea.

pathogenic fungi such as *Fomes annosus*, *Poria weirii* and *Armillaria mellea* which synthesize nitrate reductase poorly or not at all (Nelson, 1970; Hesterberg and Jurgensen, 1972).

Acidifying fertilizers, particularly the sulphates but also any N fertilizer used repeatedly, shifts litter decomposition activity to fungi (Baule and Fricker, 1970). On very fertile sites, high levels of readily available N and P may suppress mycorrhizal development by stimulating rapid assimilation of soluble carbohydrates produced in photosynthesis, thus reducing the translocation of carbohydrates to roots and some of the factors promoting fungal symbiosis (Pritchett, 1979). On less fertile sites, mycorrhizas may be scarce because nutrient deficiencies limit the production of translocatable carbohydrate. There, fertilization may improve the incidence of infection. Work by Squire *et al.* (1978) in *P. radiata* plantations in South Australia showed that multiple nutrient fertilizers increased the proportion of mycorrhizal roots on poor sites, but decreased them on sites of high quality.

Ecosystem retention of fertilizer nutrients is important, not only for extending the period of plantation growth response, but also for minimizing the contamination of lakes and streams fed by forested watersheds (Vollenweider, 1971) (see Chapter 15). Nitrate forms of N fertilizer are immediately prone to leaching. In Sweden, Tamm *et al.* (1974) showed NH_4NO_3 fertilization at 175 kg N ha^{-1} produced rapid increases in spring water NO_3^- , and concentrations remained high for 3 years. Applying urea at similar rates leads to ground water NO_3^- concentrations lower by at least an order of magnitude. Urea also produces NO_3^- , though not to the same degree as NH_4NO_3 because of biological immobilization of NH_4^+ , and chemical immobilization in humus, silicate clays, and on cation exchange sites. Only when the NH_4^+ supply exceeds rates of immobilization does nitrification increase appreciably in acid soils. Because nitrifier populations are low initially in undisturbed, coniferous forest soils (Heilman, 1974), NO_3^- production parallels population buildup until the NH_4^+ substrate is exhausted; buildup and nitrification are most rapid in the spring when soils are moist and warm. For this reason, NO_3^- loss following urea fertilization tends to be a pulse event, rather than sustained over several years (Tamm *et al.*, 1974). However, refertilization with urea leads to nitrification rates much greater than those found in previously unfertilized soils (Breuer, 1978; Johnson *et al.*, 1980), apparently because of greater numbers of nitrifiers and higher NH_4^+ levels in soils already fertilized. Urea fertilization at 224 kg N ha^{-1} on a wide range of stand and soil types in California shows that soil solution NH_4^+ concentrations rarely exceed 4 mg N l^{-1} , while NO_3^- concentrations can be much higher (Table V) although peaks in the latter occur as pulses during wet, warm periods, and will drop to control levels by the second growing season after treatment (Nakamura and Powers, 1978).

Leaching losses of NO_3^- tend to be greatest on coarse-textured, immature soils.

Because of chemical immobilization, P fertilization rarely affects ground water, except on acid quartz sands low in Fe and Al, and on organic soils low in all nutrients (Pritchett, 1979). In California, Powers *et al.* (1975) found even loamy-skeletal Xerochrepts may sorb up to $1200 \text{ kg P ha}^{-1}$ as superphosphate without appreciable changes in soil solution P, and for fine-loamy Haploxeralfs, capacities are at least 5-fold greater. Plantation fertilization on drained peatland in Scandinavia shows that autumn applications of superphosphate at 60 kg P ha^{-1} leads to ground water concentrations between 1.2 and 0.4 mg P l^{-1} in the first year after treatment, compared with 0.1 mg P l^{-1} or less for control and apatite treated plots (Tamm *et al.*, 1974).

While mineral soil is the main sink for fertilizer P (Pritchett, 1979), most fertilizer N retained in plantations of the temperate and boreal zone eventually resides in the forest floor (Miller, 1981). Incubation of soil, humus and litter collected several years after urea fertilization in northern Europe (Westman, 1974) and British Columbia (van den Driessche and Webber, 1977) show no appreciable residual effect of fertilization on soil N release, but strong residual effects in humus and litter. Thus, the forest floor acts as a major sink for added N, as well as for N derived naturally (Fig. 1).

Water availability is often a major limiting factor to plantation growth in Mediterranean environments. Early results in a *P. ponderosa* plantation in California showed that soil moisture deficiency had to be corrected before fertilizer response was possible, even on extremely N-deficient sites (Powers and Jackson, 1978). Later work in the same plantation (Table IV) showed that application of urea increased soil N availability on both poor and better sites (site indices 15 and 30 m at 50 years), but failed to appreciably affect foliar N concentrations or growth on the poor site where moisture stress was particularly high. Increasing moisture supply by clearing the woody shrubs increased tree growth, foliar N, and soil N availability. On the poor site, combining clearing with fertilization had a multiplying effect on growth. Although shrub biomass was greater on the good site, moisture availability was greater too, and treatment responses were additive.

In summary, silvicultural treatment of established stands usually leads to increased nutrient availability, either by reduced competition, or nutrient additions. Often, nitrification rates increase from the elimination of repressive factors, or increases in the supply of NH_4^+ substrate. Soil-plant reactions to treatment and their duration depend on the intensity of the treatment, the relative deficiency of the site, and the rate of stand development. Of all standard silvicultural practices considered, only prescribed burning seems to have potentially negative impacts, but no strong evidence exists that this is so.

V. HARVESTING

Harvesting removes nutrients in living biomass, the amount depending on utilization standards. Other effects are soil compaction from the movement of logs and heavy machinery over a site, accelerated decomposition of slash due to increased moisture and temperature of the forest floor, and losses of nutrients through leaching.

A. Nutrient Losses by Biomass Removal

Amounts of nutrients removed during harvest depends on utilization standards, tree species, stand development and site quality. Stone (1975) estimated that nutrients removed by harvesting stemwood and bark generally are 50–300 kg N ha⁻¹, 10–30 kg P ha⁻¹, and 100–1000 kg Ca ha⁻¹. These amounts could be multiplied 2 to 3 times as conventional above-ground tree harvesting techniques are replaced by whole-tree harvesting where even roots may be removed. Implications of whole-tree harvest techniques and shorter rotations on nutrient removals also are discussed in reviews by Boyle and Ek (1972), Weetman and Webber (1972) and Wells and Jorgensen (1979).

Because net primary productivity is highest in wet tropical and subtropical forests and lower in broad-leaved and coniferous forests of the temperate zone, the sum of mineral elements in the biomass of tropical forests is often twice as great as in broad-leaved temperate forests and triple that in many temperate conifer forests (Rodin and Bazilevich, 1967). Also, the relative proportion of nutrients in biomass above ground is greatest in the tropics, and nutrient storage in the forest floor is very low (Fig. 1). Thus, more nutrients are removed in whole-tree harvesting in the tropics than in the temperate zone, and site quality reductions could be greatest there. Similarly, whole-tree harvesting of a deciduous forest generally removes more nutrients than harvesting evergreens of similar biomass, unless the harvest occurs after leaf fall. For example, stands of *Populus*, *Picea* and two pine species (*P. resinosa* and *P. banksiana*) having similar biomass and growing on nearly identical sites were examined by Alban *et al.* (1978). *Populus* and *Picea* held high proportions of total ecosystem-Ca in their forest floor and stand biomass, whereas most of the Ca in *Pinus* ecosystems was contained in the mineral soil. Harvesting the pines would remove less Ca from the site than harvesting the hardwoods.

Plantations of *P. radiata* in Australia, however, are more demanding of the

site than are native *Eucalyptus* hardwoods, particularly as the pine grows faster and its rotation length is shorter. Harvesting a 40-year rotation of *P. radiata* removes 4.5 times more P than harvesting a 57-year rotation of *E. delegatensis* (197 vs 44 kg P ha⁻¹). When the rotation length is reduced to 18 years, P removal by pine is 5.7 times greater than by the 57-year *Eucalyptus* rotation (214 vs 44 kg P ha⁻¹) (Crane and Raison, 1981). In New Zealand, conversion of *Leptospermum scoparium* to *P. radiata* has changed chemical characteristics of the soil after 45 years; higher titratable Al and lower exchangeable Ca, Mg, total-N and organic-P occurred in the A₂ horizon (McIntosh, 1980).

Intensive plantation management could also lead to greater nutrient loss through leaching and erosion because it implies shorter rotations and thus more frequent site disturbance (Armson, 1977). The extra nutrients removed by whole-tree harvesting is similar to that of litter utilization in Europe. Kreutzer (1979) concluded that continuous, intensive, full-tree utilization may depress site quality on one-third of the forested area of southern Germany. However, exact criteria for critical examinations are not available.

Rotation length is an important factor determining nutrient removal, even under low utilization. Shortened rotations mean a greater proportion of the rotation length is spent in site preparation and the period before full site occupancy, when forest floor disturbance is greatest and nutrient losses often are high (Webber, 1978). Also, nutrient retention in perennial tree parts parallels the trend in biomass growth (Switzer and Nelson, 1972; Wells and Jorgensen, 1979), peaking around crown closure, and dropping in concentration with time (Madgwick *et al.*, 1977). Thus, more nutrients will be removed in several short rotations than in an equivalent harvest in a longer rotation. In Australia, Mitchell (1970) compared expected losses of N and P from two 20-year rotations and from one 40-year rotation with five thinnings for *P. radiata* on podzolized sands. Estimated losses were 284 kg N ha⁻¹ and 24 kg P ha⁻¹ for the one 40-year rotation, and 336 kg N ha⁻¹ and 28 kg P ha⁻¹ for the two 20-year rotations, i.e. increased losses of 18% N and P. Squire and Flinn (1981) estimate that about 18% of the total ecosystem N is removed in harvesting the boles plus bark of *P. radiata*, but if whole-tree harvesting is implemented (which involves removal of crowns also), about 25% of the N would be removed. Combined effects of utilization standards and rotation length on nutrient drain also are demonstrated by Switzer and Nelson (1972) for *P. taeda* plantations in the USA. Two 20-year whole-tree rotations would remove 66% more N, 93% more P, 45% more K, and 34% more Ca than one 40-year rotation with stem-harvest. As more nutrients are removed in the harvest, more kinds of fertilizers are required. This sequence produces multiple nutrient deficiencies, and increases the difficulty of predicting the effects of nutrient removal on soil reserves (Wells and Jorgensen, 1979).

Utilization standards also make a considerable difference in nutrient export. Because foliage and branches constitute a larger share of the total biomass and nutrient capital in younger trees, whole-tree harvesting in a young plantation would remove more nutrients annually than at a later age (Wells and Jorgensen, 1979).

Conclusions regarding the outcome of nutrient removal on site quality are largely theoretical (see also Chapter 17). While site nutrient evaluation through analysis of overall mineral cycles is an attractive approach, at present there is neither an adequate framework nor sufficient information to judge the outcome of shortened rotations and high utilization with certainty. Although nutrient outputs can be measured with fair precision, true rates of nutrient input from hydrological, biological and geological sources are understood poorly. Nevertheless, risks seem greatest on poor site plantations managed under short rotations with whole tree harvesting, and in tropical plantations where the absence of a forest floor makes them poorly buffered against fertility loss from repeated harvest. Effects of harvesting and other management practices on proton balance in forest soils and their consequences on soil properties are discussed in Chapter 4.

B. Nutrient Losses by Leaching

An understanding of factors controlling nutrient release and movement is necessary to compare the effects of forest practices on nutrient status of different sites. The importance of the soil and rainfall, for example, was shown in a study in the Berkeley Hills, California (McColl, 1978). There, soil solution concentrations of K^+ , Ca^{2+} , Mg^{2+} , NO_3^- and HCO_3^- decreased following clearcutting a *Eucalyptus globulus* plantation, conflicting with the increases generally noted in other studies (Tamm *et al.*, 1974; Vitousek, 1981), but largely explainable by soil and climatic conditions. The soil there was a Typic Argixeroll (a clay-loam with a high cation exchange capacity), rainfall was both low (568 mm yr^{-1}) and seasonal (usually December to March). Much of the slash and litter was removed during harvest. Mineralization of organic matter was minimal, as was ammonification of organic N. Cations were retained on the soil exchange complex. Low soil moisture, coupled with no appreciable increase in NH_4^+ , limited nitrification and prevented deep leaching of NO_3^- (Table VI). In most cases, however, soil cation exchange capacities are lower and precipitation is higher, and nutrient concentrations in the soil solution increase following harvesting. For example, at Challenge Experimental Forest in the foothills of the Sierra Nevada, California, clearcutting increased NO_3^- concentrations of the soil solution (Table VI). Here, the rainfall over the same months was greater (1460 mm)

Table VI. Nitrate concentrations in soil solution in clearcut and uncut forests of *Eucalyptus globulus* in the Berkeley Hills^a and *Pinus/Abies/Pseudotsuga* in the Sierra Nevada, California.^a

Soil depth	Nitrate concentrations in the soil solution					
	Berkeley Hills, California ^b			Sierra Nevada, California ^c		
	Control ($\mu\text{eq l}^{-1}$)	Clearcut	Change (%)	Control ($\mu\text{eq l}^{-1}$)	Clearcut	Change (%)
Surface	245.5	55.4	-77.4	11.4	29.3	157.0
Subsurface	122.7	122.3	-0.6	8.6	12.9	50.0

^a Berkeley Hills site: low rainfall, high exchange capacity of soil. Sierra Nevada site: high rainfall, low exchange capacity of soil. Data are arithmetic means for samples collected during the first hydrologic year following clearcutting.

^bFrom McColl (1978).

^cFrom Powers and McColl, unpublished.

and the soil was an Ultic Haploxeralf with lower exchange capacity developed on highly weathered gabbro-diorite. Greater soil moisture and the abundance of fresh organic matter stimulated mineralization and nitrification, resulting in leaching of NO_3^- and cations.

Studies quantifying nutrient losses by leaching following harvesting have employed small watersheds where inputs and outputs are monitored, and lysimeters in small plots. While these techniques are not necessarily equivalent, both have given information needed to calculate net losses of nutrient ions to drainage waters. For example, Gessel and Cole (1965), using tension-plate lysimeters beneath a clearcut *Pseudotsuga menziesii* plantation in Washington, found mobility of N, K and Ca increased in the upper soil profile, but that losses of these elements were minimal beyond the rooting zone. During the first year after clearcutting only 0.5, 0.1 and 4.9 kg ha⁻¹ more N, K and Ca were lost to drainage waters, compared with the control. In contrast, leaching losses from a clearcut and herbicide-sprayed deciduous hardwood watershed in New Hampshire were much greater (Likens *et al.*, 1970). During the first year, revegetation increased NO_3^- , K and Ca losses by 100, 20, 68 kg ha⁻¹ respectively. In New Hampshire, nitrification rates were accelerated by clearcutting, and herbicides prevented plant regrowth and uptake of nutrients released from decomposing slash. These results were exceptional, as nutrient losses to drainage water are usually negligible following clearcutting (Douglass and Swank, 1972; Tamm *et al.*, 1974; McColl, 1978). The data illustrate the importance of biological cycling in conserving soil nutrients. Leaching losses after clearcutting rarely threaten the productivity of subsequent plantations, although nutrient levels in streams may rise temporarily and exceed acceptable standards following

clearcutting. Losses from a site following clearcutting are discussed also in Chapter 15.

Besides ionic leaching, organic substances may be leached into drainage waters where management practices produce large amounts of organic residues. Hart *et al.* (1980) found that phenol concentrations under finely divided wood and bark residues greatly exceeded allowable aquatic standards 2 years after clearcutting (Table I). Low NO_3^- concentrations under chipped slash suggest that harvest residues may be manipulated to control nitrification. However, the effects of residue leachates on ammonification have not been reported.

C. Nutrient Losses by Erosion

Erosion in forests has been documented thoroughly (Swanston and Swanson, 1976). Of the two main types of erosion, surface and mass-flow, the latter is more common and serious following timber harvesting (see also Chapter 15).

Surface erosion in undisturbed forests causes losses of about $100 \text{ g ha}^{-1} \text{ yr}^{-1}$ of N and Ca, and $25 \text{ g ha}^{-1} \text{ yr}^{-1}$ of Mg and K (McColl and Grigal, 1979) and are at least an order of magnitude less than deep-leaching losses from most undisturbed forests (Stone, 1973). Because soils sorb P so effectively, soil erosion is generally the main means of soil P loss. For example, Duffy *et al.* (1978), studying unfertilized pine plantations in the southern USA, found that the yield of P in solution from five forested watersheds during the hydrologic year averaged 88 g ha^{-1} , whereas P in eroded sediment was 2.4 times greater. Accelerated surface erosion is linked mainly to road construction and secondarily, to the harvest itself. Erosion declines exponentially with time (Megahan, 1974), decreasing most rapidly in the first 2–5 years. A broad estimate for soil loss by surface erosion over a 5–10-year period following road building and harvesting is between 500 and $1000 \text{ kg ha}^{-1} \text{ yr}^{-1}$. Accompanying nutrient losses may equal those from deep leaching under natural conditions.

Evaluating rates of natural erosion is difficult because they often are very slow, and infrequent, unpredictable storms may trigger major losses (McColl and Grigal, 1979). Roads also contribute heavily. Dyrness (1967) attributed 72% of the mass erosion following a severe storm in Oregon to roads, which occupied only 2% of the area. Logging also may add to mass erosion both through increased soil water from reduced transpiration, and through losses in living root mass which helps hold unstable soils in place (Rice *et al.*, 1972).

Harvesting effects are not limited to surface horizons where physical disturbances are obvious. Lower soil horizons usually retain greater moisture

following forest cutting because of decreased transpiration. For example, during dry seasons of 1975 and 1976, McColl (1977) found that soil moisture increased from about 18 to 28% (-2.0 MPa to -1.2 MPa) at soil depths of 30 to 75 cm in a clearcut, whereas soil moisture averaged about 10% (about -6.5 MPa) at all depths in an adjoining *Eucalyptus* plantation. High soil moisture levels may favour denitrification and SO_4^{2-} reduction to H_2S , and increase the mobility of certain nutrients such as Fe and Mn (McColl, 1978).

Plantations on steep slopes must be established quickly following harvesting, as soil moisture buildup could decrease stability and cause landslides (Gray, 1970; Brown and Shue, 1975). The shear resistance of soils also is decreased once roots of felled trees decompose, although this may take a decade or more (Endo and Tsuruta, 1969).

Effects of nutrient losses by leaching and erosion on site productivity are difficult to assess, because the magnitudes of all ecosystem inputs, outputs and components are not generally known. Rates of rock weathering usually are estimated by differences in mass-balancing of nutrient budgets, rather than being measured directly (Clayton, 1979; Chapter 4). Often, atmospheric inputs can be significant (see Chapter 3).

D. Soil Compaction

During plantation thinning or harvesting, the movement of logs across the surface of the ground and heavy machinery (roading and logging) disturb the litter layer, gouge and rut the mineral soil, and may compact the upper layers of the profile. These effects have been reviewed by Greacen and Sands (1980).

When soil is compacted, pore volume is reduced and bulk density is increased. Thus, soil aeration, water infiltration and saturated hydraulic conductivity are decreased and soil strength increased accordingly (Fig. 2). Such changes may seriously affect the growth of an existing stand, or the establishment and growth of a new stand (Fig. 3), although experimental data are rare. Consequences include increased surface runoff and accompanying erosion, reduced root penetration, and less available soil moisture and oxygen.

The complexity of controlling highly variable field factors make prediction of soil compaction effects very difficult. In the Mount Gambier region of South Australia, planted extensively to *P. radiata* a typical, non-compacted sandy soil at 10 to 40 cm depth has a bulk density of 1.35 g cm^{-3} . A bulk density of 1.60 g cm^{-3} occurs with extreme compaction, but bulk densities of 1.48 g cm^{-3} are common (Sands *et al.*, 1979). Sands and Bowen (1978)

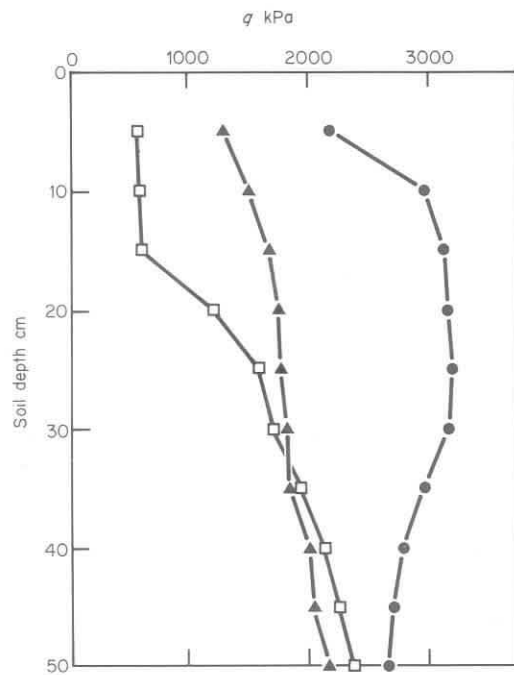


Fig. 2. Changes in soil strength q (kPa) with depth (cm) of Mt Burr sand on a logging road (●), after 10 passes with a JD 740 rubber-tyred skidder pulling full-length logs of radiata pine (▲), and adjacent undisturbed soil (□). (Each point was the mean of six observations, and q was measured as resistance to a penetrometer.) From Greacen and Sands (1980).

concluded that bulk densities in the range of 1.35 to 1.60 g cm^{-3} can significantly reduce root growth in *P. radiata*. However, if the soil is still able to provide sufficient air, water and nutrients to the tree roots, then shoot growth would not be decreased (Greacen and Sands, 1980).

Although reports on the long-term effects of compaction on forest productivity are rare, some have related tree growth to soil bulk density. Squire *et al.* (1978) showed that root concentration of *P. radiata* in northeastern Victoria, Australia decreased with increasing soil bulk density over the range 1.1 to 1.4 g cm^{-3} . Squire and Flinn (1981) concluded that compaction during harvesting could reduce *P. radiata* growth. On infertile soils particularly, nutrient availability would be lessened. Soils low in organic matter are more susceptible to compaction and increased bulk density, thus it is very important to maintain organic matter levels during management practices (Greacen and Sands, 1980).

Forestry and agriculture contrast strikingly in soil compaction problems.

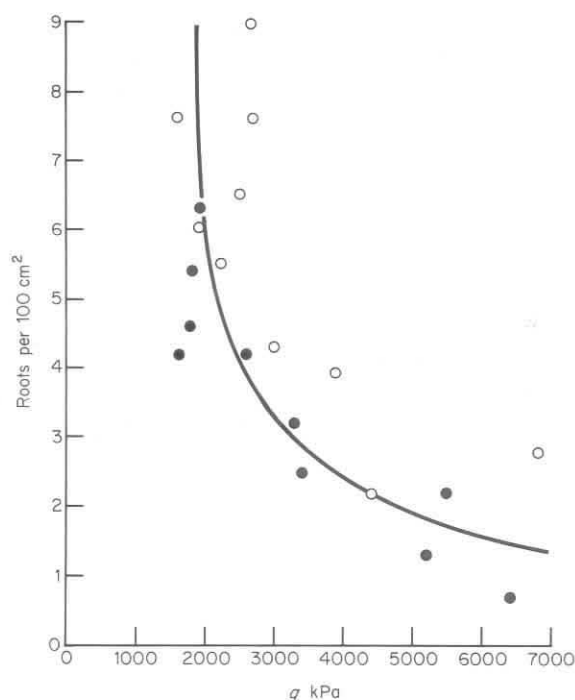


Fig. 3. The relationship between frequency of roots (number per 100 cm²) of radiata pine and soil strength q (kPa) of Mt Burr sand (○) and Young Sand (●). (q was measured as resistance to a penetrometer.) From Greacen and Sands (1980).

In agriculture, ploughing or other practices ameliorating compaction are usually applied regularly with crop rotations. In forests, however, treatments are far less frequent and crop rotations are much longer. One of the major differences and most distressing problems of forest soil compaction is the longevity of effect. The length of recovery from compaction varies with soil type and the degree of compaction. Sandy soils low in organic matter, once compacted, may never return to their original state unless major physical disturbance and incorporation of organic matter is practised. Estimates of recovery time vary from about 5 to 20 years, although recovery times might be longer for log-extraction roads and landings. For example, 50-year-old extraction tracks on sandy soils of *P. radiata* plantations in South Australia still are more compact than surrounding soils (Greacen and Sands, 1980). Even if such compaction is overcome eventually, serious growth may be lost because of retardation during early stand development.

The key to solving soil compaction problems is to avoid or minimize disturbance of the litter layer and upper mineral soil containing organic

matter, particularly in sandy soils and in wet conditions. Carefully planned traffic control during harvesting should be implemented, and severe burns should be avoided to prevent organic matter loss. Mechanical loosening of soil and addition of organic matter are costly, but may be effective remedial practices in compacted areas.

VI. SITE QUALITY DECLINE

In some areas in South Africa, Australia and New Zealand, conifer monoculture has produced high yields in the first rotation but lower yields in the second (Stone and Will, 1965; Keeves, 1966). This problem had raised particular concern in South Australia where *P. radiata* plantations are grown on infertile sandy soils (Fig. 4).

First rotation
1932 plantation

Second rotation
1952 plantation

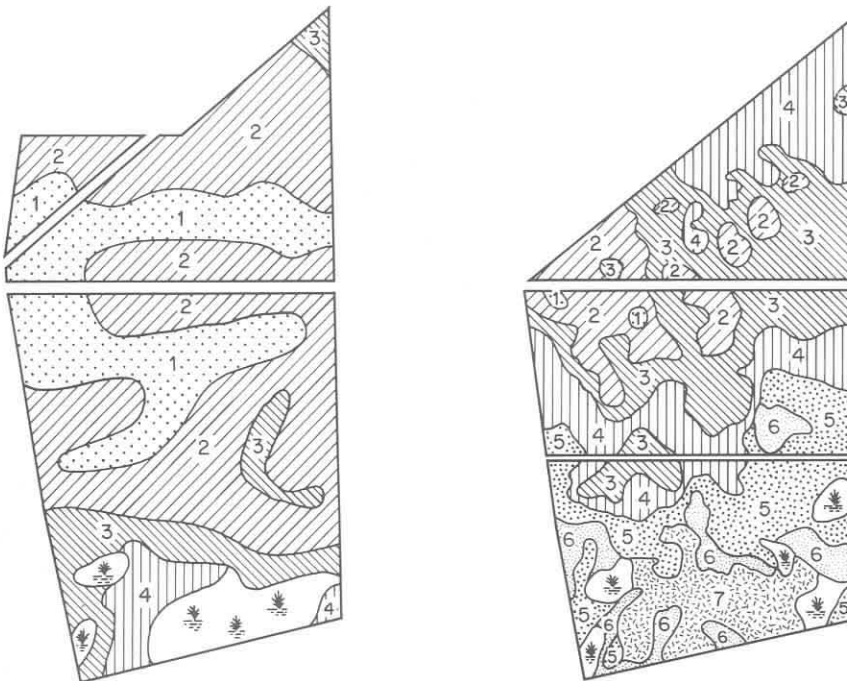


Fig. 4. Mappings of site class for an area of Penola Forest Reserve, South Australia, for the first and second rotations of *Pinus radiata*. Numbers 1–7 indicate site quality scales representing total production 1500 (SQ1)–400 (SQ7) $\text{m}^3 \text{ha}^{-1}$ over 50 years. From Boardman (1978).

Young conifer stands immobilize N at about $8\text{--}12\text{ kg ha}^{-1}\text{ yr}^{-1}$, and the nutrient supply in the soil may not keep pace with forest demand (Stone and Will, 1965). Further, conifer litter tends to decompose more slowly than does litter from hardwoods. A decreasing availability of N and S, plus high soil acidity, keeps much of the organic matter intact, immobilizes nutrients, and leads to a mor-type humus. Whyte (1973) found greatest growth depression on shallow soils of ridges and slopes in New Zealand. Such sites are more droughty, further reducing turnover of organic matter.

In southeastern Australia, Hamilton (1965) studied *P. radiata* plantations on dry, coarse-textured soils previously supporting sclerophyll *Eucalyptus* woodland. Soils under pine had higher bulk densities and C:N ratios, lower organic matter, less N, and more cation leaching from the A to the B horizon, than did soils beneath *Eucalyptus*. These results differ from those of more fertile pine plantations in Wisconsin (Wilde, 1964).

Stone and Will (1965) suggested that N deficiency in second-rotation plantations of *P. radiata* in New Zealand relates to changes in soil microbial reactions when pines are introduced. The root complex and associated microflora of pine apparently can break down fractions of soil organic matter resistant to native vegetation, but N made available is depleted by the first rotation crop. Similarly, in New York, Fisher and Stone (1969) studied the N and P contents of herbaceous vegetation and soil across the boundary of pine and larch plantations and the open, abandoned fields in which they were planted. They concluded that the conifer rhizosphere mineralizes or otherwise extracts some organic fraction of soil N that had been resistant to microbial action under the previous vegetation. Robinson (1973) found that the number of mycorrhizal roots and degree of infection were less in second rotations of *P. patula* in Swaziland. He suggested that substances toxic to symbiotic fungi build up in the pine litter. Perhaps this is analogous to the "soil fatigue" noted in European stands of *Abies alba* (silver fir), where young stands regenerate naturally, but older stands do not (Maliszeweska and Moreau, 1959). There, soil microflora were reported to be abundant in young plantations, but not in older.

Although fertilization with N and P can greatly increase productivity of *P. radiata* in South Australia (Woods, 1976), Sands *et al.* (1979) suggested that site deterioration should also be considered in terms of soil structure as influenced by organic matter. Organic matter removal, either by mechanical means or by burning, leads to reduced cation exchange capacity and water-holding capacity, as well as to increased soil compaction. These changes are particularly detrimental on poor sites.

The problem of second rotation decline obviously is complex, but is mainly determined by characteristics of soil. Sandy soils with low organic matter and N may need special attention (Squire and Flinn, 1981).

However, many factors act in concert with no single causal factor (Boardman, 1978).

Second-rotation site-quality decline is not a common phenomenon (Evans, 1976), although the few reported cases provide a warning. Florence and Lamb (1975) do not believe that the decline will occur in Australia other than in South Australia's sandy soils because in most other pine plantations the soil is generally more fertile. Where second rotation decline is found, it can largely be traced to mismanagement stemming from a lack of understanding. Even in these cases, sound management, particularly weed control and fertilization, is likely to correct the problem (Will and Ballard, 1976; Woods, 1976).

VII. CONCLUSIONS

Forest management practices produce both short and long-term changes in chemical, physical and biological soil properties. Consequences of these changes on the processes affecting plantation development may be temporary or lasting. To date, much of the research emphasis in plantation forestry has focussed on narrowly-defined objectives, such as seedling survival or growth responses to silvicultural treatments. Integrated process studies involving interactions between biotic and abiotic ecosystem components are rare and mainly restricted to unmanipulated stands. Research is needed to identify unifying principles that govern transformation and flow of nutrients and other matter in intensively-managed plantations (see Chapter 4).

One theme emerging from past studies is that the forest floor and surface soil serve as major buffers against change, particularly in temperate and boreal forests. Forest floor and surface soils are important nutrient sinks and management techniques can increase or decrease nutrient availability and site productivity. The forest floor is particularly dynamic and resilient in this respect because it is altered readily by many forest practices, yet renews itself to some extent as long as vegetation persists. Practices that deplete the forest floor (burning, raking, high utilization) may decrease site productivity, but effects on yield may only be evident in subsequent rotations (see Chapter 4). In contrast, surface soil depletion through mechanical displacement or erosion may degrade site quality swiftly and lastingly.

Practices progressively reducing the forest floor probably will prove detrimental on poor sites, particularly boreal plantations with shallow or coarse-textured soils. However, the same practices may have little effect on growth on fertile sites. Viewed individually, practices discussed appear to have little lasting effect on sustained productivity at a site, but together may

produce additive or synergistic effects. Attention should be directed to effects of intensive silviculture and greater utilization standards on short rotation plantations where nutrients are near levels critical to sustained productivity.

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